SUPPLEMENTAL MATERIALS

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Dynamic Resilience Quantification of Hydropower Infrastructure in Multihazard Environments

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PAPER SUPPLEMENTARY MATERIALS

CHEAKAMUS RESILIENCE-CENTRIC SD MODEL COMPONENTS RELATIONSHIPS

This section presents the details of the six integrated modules for the Cheakamus resilience-centric SD model including, the definition of each module component and the mathematical equations that define the relations between the system components.

Hydraulic Module

The hydraulic module, shown in **Figure S1**, represents the hydraulic system components that affect the hydraulic status of the hydropower dam during the operational period. These components are summarised, as shown in **Table S1.**

Table S1. Dynamic variables used in the hydraulic module equations

Dynamic Variables	Symbol
Reservoir storage	$\boldsymbol{RS\ (m^3/s)}$
Inflow	$\boldsymbol{IF\ (m^3/s)}$
Outflow	$\boldsymbol{OF\ (m^3/s)}$
Reservoir Level	***RL (m)***
Spillway Gate Release	$\boldsymbol{SGR\ (m^3/s)}$
Breach flow	$\boldsymbol{BF\ (m^3/s)}$
Penstock leakage	$\boldsymbol{PL\ (m^3/s)}$
Power flow release	$\boldsymbol{PF\ (m^3/s)}$
Overtopping flow	$\boldsymbol{OT\ (m^3/s)}$
Unobstructed gate flow	$\boldsymbol{UGF\ (m^3/s)}$
Intake gate	***IG (binary)***
Gate capacity	***GC (%)***
Dam breach trigger	***DBT (binary)***
Dam breach triger level	***DBTL (m)***

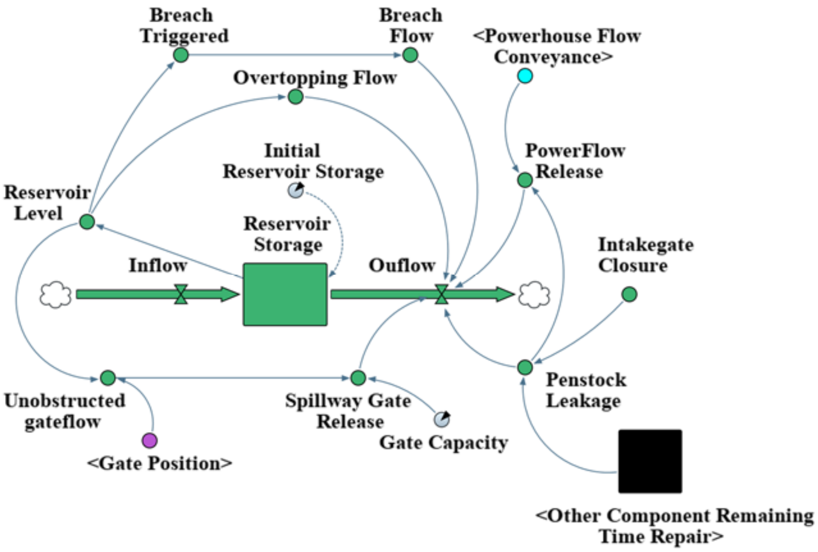

Fig. S1 Hydraulic Module components

This module represents reservoir storage *"RS"* as a stock, where the input is the inflow *"IF" and* the output is the outflow *"OF"*, as shown in **Eq. S1**. *RS* can also be determined using the stage storage curve as function in reservoir water level *"RL"*, as shown in **Eq. S2.**

$$\frac{d(RS)}{dt} = IF - OF \qquad Eq.S1$$

$$RL = Stage\ Storage\ curve\ (RS) \qquad Eq.S2$$

IF is considered as input data to the SD model. It should be noted that in this study, historical inflow data is used in the validation and resilience quantification process. On the other hand, *OF* is determined as the summation of five outflow components, including Spillway Gate Release *"SGR"*, breach flow *"BF"*, Penstock leakage *"PL"*, Power flow release *"PF"*, Overtopping flow *"OT"*, as shown in **Eq. S3**.

$$OF = SGR + BF + PL + PF + OF \qquad Eq.S3$$

SGR represents the Unobstructed gate flow *"UGF"*, considering the real-time Gate capacity *"GC"*, as shown in **Eq. S4**. *UGF* is the gate flow in the case of no debris (i.e., GC= 100%), which can be determined using the gates rating curves as a function in reservoir water level *"RL"* and the gate position *"GP"* (determined by the gate actuator module), as shown in **Eq. S5**.

$$SGR = UGF \ x \ GC \qquad Eq.S4$$

$$UGF = Gates\ rating\ curve\ (RL, GP) \qquad Eq.S5$$

BF is defined by the full reservoir storage when a dam breach is triggered *"DBT"* (when the dam is breached, the reservoir is completely emptied). Dam breach is usually triggered when the reservoir water level exceeds a particular level *"DBTL"* above the earth dam crest. In this study, *DBTL* is assumed to be 381.73m, according to King, 2020. *DBT* is a binary value of 1 for breached and zero for not breached, as shown in **Eq. S6** and **S7**.

$$if\ (RL > DBTL): DBT = 1;\ else: DBT = 0 \qquad Eq.S6$$

$$if\ (DBT = 1): BF = RS;\ else: BF = 0 \qquad Eq.S7$$

PL is defined as the leakage flow occurred if the penstock is failed (i.e., Penstock rupture). Penstock rupture is initiated by the hazard sector (according to hazard impacts), where PL is equal to the Headcover max flow *"HCMF"* when the penstock rupture remaining repair time *"PsRrt"* is larger than zero. As shown in **Eq. S8**, *PL* also depends on the status of the Intake gate *"IG"*, where zero means the gate is open, and one means the gate is closed. The intake gate is usually placed at the upper stream end of the power flow conduit, where it is closed to reduce the negative impact of the excessive flows resulting from the penstock rupture (i.e., *PsRrt* > 0) or head cover failure (i.e., *HcRrt* > 0). The closure of the intake gate also depends on *RL*, where *RL* must reach an elevation below the sill of the *IG* (363.06 m) to be closed, as shown in **Eq. S9**.

$$if\ (PsRrt > 0\ \&\&\ IG = 0): PL = HCMF;\ \ else: PL = 0 \qquad Eq.S8$$

$$if\ (PsRt > 0\ \ or\ HcRrt > 0): (if\ (RL < 363.06): IG = 1;\ else: IG = 0);\ else: IG = 0 \quad Eq.S9$$

PF is defined by the flow transferred to the powerhouse (powerhouse flow conveyance *"PHFC"*), as determined by the turbine actuator sector, considering reduction that may occur due to the escaping flow of penstock leakage *PL* (if the penstock fails). *IG* status also affects the *PF*, where *IG* might be closed to empty the powerhouse for penstock or headcover maintenance, as shown in **Eq. S10**.

$$if\ (IG = 0): PF = PFC - PL;\ else: PF = 0 \qquad Eq.S10$$

OF is determined using the overflow stage-discharge curve, stated in BC. Hydro, 2005, as a function in *RL* to determine the total overflow discharge passing over the reservoir's free-overflow weirs or/and saddle dams or/and main earth dam.

$$OT = Overflow\ stage\ discharge\ curve\ (RL) \qquad Eq.S11$$

Sensor Module

The sensor module, shown in **Fig. S2**, represents the collection and transmission process of the hydraulic variables from the hydraulic module to the operation module. These components are summarised, as shown in **Table S2.**

Table S2. Sensor module dynamic variables

Dynamic Variables	**Symbol**
Sensor condition	***SC (binary)***
Gauge reading	***GR (m)***
Gauge reading errors	***GRE (%)***
Gauge Processing	***GP (binary)***
Gauge relay	***Grl (m)***
PLCRTU	***PLCRTU (binary)***

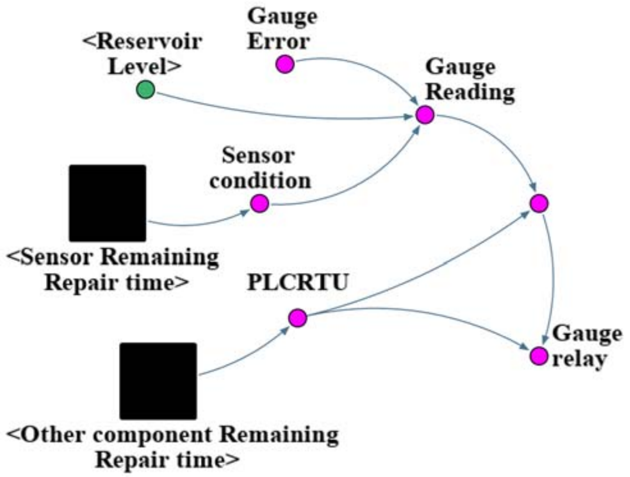

Fig. S2 Sensor Module components

As long as the sensors are properly functioning, gauge reading *"GR"* records *RL* considering the gauge reading errors *"GRE"*, as shown in **Eq. S12 and S13**.

$$if\ (SRrt > 0): SC = 0; else\ SC = 1 \qquad Eq.S12$$

$$if\ (SC = 1): GR = RL + \left(\frac{GRE}{100}\right)\ x\ RL;\ \ else: GR = -1000 \qquad Eq.S13$$

The gauge processing *"GP"* node represents the interpretation of the collected data processed by *PLC*. If the *PLC* is working properly, the collected data is sent to the operation sector through the gauge relay *"GRl"*. The gauge relay is carried out by a remote terminal unit *RTU*. In this model, the communication tools, including *RTU* and *PLC,* are modeled as one variable, *"PLCRTU"*, where the multi-hazard module determines the repair time for this component according to the hazard impact. The following **Eq. S14 and S15** describe the previous system components process.

$$if\ (PLCRTURrt > 0): PLCRTU = 0; else\ PLCRTU = 1 \qquad Eq.S14$$

$$if\ (PLCRTU = 0): GP = -1000, GRl = -1000;\ \ else: GP = GR, GRl = GR \qquad Eq.S15$$

<u>OPERATION MODULE</u>

The operation module, shown in **Fig. S3**, is responsible for determining the turbine and gate instructions, considering the current and expected dam hydraulic status and the operational targets. The operation module components are summarised in **Table S3.**

Table S3. Operation module dynamic variables

Dynamic Variables	Symbol
Turbine instruction	***TI (m3/s)***
Gate instruction	***GI (m)***
Forecasted inflow for the next 14 days	$IF_{forecasted}$ (m^3/s)
Max. & Min. Reservoir level for the next 14 days	$RL_{Limits}(m)$
Fish flow for the next 14 days	FF (m^3/s)
Manual actuation	***MA (binary)***
Manual actuation initiated	***MAI (days)***
Initiate	***Int (days)***
Site staff mobilized	***SSM (binary)***
Demobilized	***DM(days)***
Site staff notified	***SSN (binary)***
Contacting initiation	***CI (days)***
Contacting delays	***CD (days)***
Contacting remaining time	***Crt (days)***
Contacting	***CO (days)***
Accessing site remaining time	***ASrt (days)***
Mobilizing Initation	***MI (days)***
Mobilizing	***MO (days)***
Accessing delays	***AD (days)***

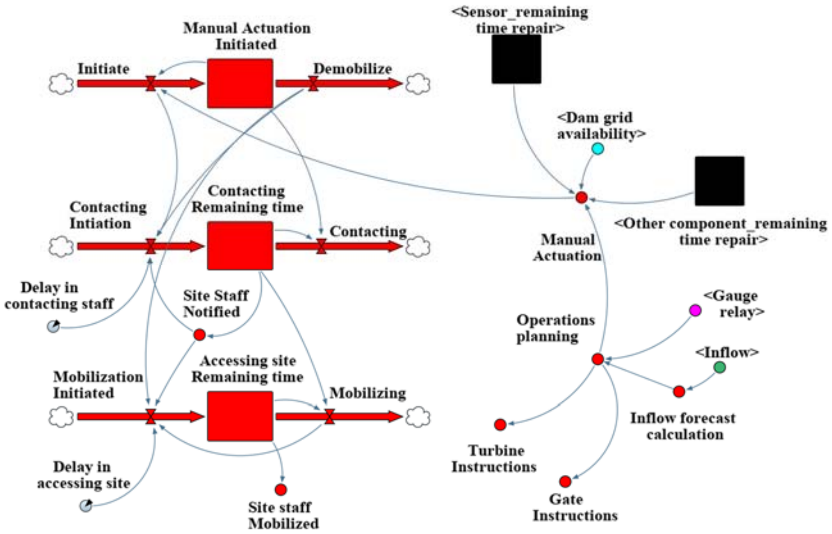

Fig. S3 Operation Module components

The gate *“GI”* and turbine *“TI”* instructions are determined by the Operations planning algorithm, which aims to maximize power releases and ensure the minimum gate releases (i.e., fish flow). The operations planning algorithm, adopted from King et al., 2020, initially sets the gate releases equal to the fish flow, while the remaining inflow discharge is directed to the turbines with a maximum power flow is 65 m^3/s. Using the inflow forecasts “$\boldsymbol{IF_{forecasted}}$”, reservoir level limits (i.e., MNRL, MaNRL, MRL, MaRL), and fish flow demand for the next 14-day, the algorithm adjusts the initial gates and turbine releases over the 14-day window to maintain the *RL* within the normal operating range (detailed operation planning algorithm can be found in King, 2020). In this study, the model utilizes the historical Daisy Lake inflow data for the forecasted reservoir inflow. However, this forecasted inflow can be more realistically alternatively predicted using the climate forecasts and watershed models to determine the effect of climate change.

In the absence of hazards, gates usually operate remotely. However, hazards may impact the communication tools *PLCRTU* or sensors. Subsequently, manual actuation *"MA"* should be initiated until the *PLCRTU* or the sensors are returned to service, as shown in **Eq. S16**.

$$if\ (SRrt > 0\ Or\ PLCRTURrt > 0): MA = 1; else: MA = 0 \qquad Eq.S16$$

The manual actuation initiation process is represented by a stock *"MAI"* with an inflow is initiate "*Int"*, and the outflow is demobilization *"DM"*. *DM* is set to zero when the site staff is mobilized, and manual actuation is no longer required, as shown in **Eq. S17 and S18**.

$$if\ (MA = 1\ and\ MAI = 0): Int = 1; else: Int = 0 \qquad Eq. S17$$

$$if\ (SSM = 1\ and\ MA = 0): DM = 1; else: DM = 0 \qquad Eq. S18$$

The mobilization process for the site staff starts by notifying the plant manager to contact the site staff to be mobilized. As such, the contacting process is represented by stock to represent the remaining time to notify the plant manager and contact site staff *"Crt",* where its inflow is the contact initiation *"CI"* and its outflow is contacting *"CO"*. The contacting process is represented to simulate any delay in the contact process *"CD"*. Once the *Crt* stock is drained (i.e., *Crt* = 0), the site staff *"SSN"* is considered to be notified and despatched to the site, as shown in **Eq. S19, S20, S21**.

$$if\ (Int = 1\ and\ SSM = 0\ and\ SSN = 0): CI = CD; else : CI = 0 \qquad Eq. S19$$

$$if\ (Crt > 0\ and\ MAI = 1): CO = 1; else: CO = 0 \qquad Eq. S20$$

$$if\ (MA = 1\ and\ Crt = 0): SSN = 1; else: SSN = 0 \qquad Eq. S21$$

As the site staff is being notified, the model mimics the process of accessing the site. The accessing process is represented as a stock of accessing site remaining time *"ASrt"* with an inflow of mobilization initiation *"MOBI"* and outflow of mobilizing *"MOB"*. The accessing process is represented to consider any access delays for the site staff *"AD"*. Once the *ASrt* stock is drained, the site staff is considered to be mobilized, as shown in **Eq. S22, S23, and S24.**

$$if\ (ASrt > 0\ and\ SSM = 0\ and\ SSN = 1): MOBI = AD; else : MOBI = 0 \qquad Eq. S22$$

$$if\ (ASrt > 0\ and\ SSM = 0): MOB = 1; else: MOB = 0 \qquad Eq.S23$$

$$if\ (ASrt = 0\ and\ MAI = 1): SSM = 1;\ else: SSM = 0 \qquad Eq.S24$$

ACTUATOR MODULE

GATE ACTUATOR MODULE

The gate actuator module, shown in **Fig. S4**, represents spillway gate components, which interact to adjust the spillway gate position according to the gate instructions. The gate actuator module components are summarised in **Table S4.**

Table S4. Gate actuator module dynamic variables

Dynamic Variables	Symbol
Gate failed in place	***Fip (binary)***
Gate collapse	***Fcoll (binary)***
Gate closed	***Fc (binary)***
Gate availability	***GA (binary)***
Gate power supply	***GPS (binary)***
Gate Position	***GP (m)***
Maximum opening	***MP (m)***
Last gate position	***LGP (m)***

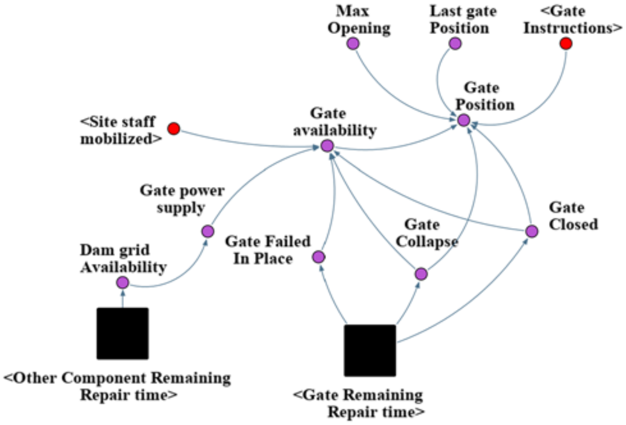

Fig. S4 Gate Actuator Module components

This module represents two main nodes, Gate availability *"GA"* and Gate position *"GP"*. *GA* is determined based on the gate components affected by hazard impact. Generally, Gate components failures lead to three types of gate failure (binary): 1) Gate remains in the closed position *"Fc"*; 2) Gate sticks in its current position *"Fip"*; 3) Gate collapses *"Fcoll"*. According to the hazard impact, these three types of failures are initiated, and the required repair time by the multi-hazard module. *GA* is also affected by the gate power supply *"GPS"* status, depending on dam grid availability. Moreover, in the case of manual actuation, Site staff should be mobilized to consider the gate is available, as shown in **Eq. S25 and S26**.

$$If\ (MA = 0){:}\ if\ (Fc = 0\ \&Fcoll = 0\ \&Fip = 0\ \&GPS = 1){:}\ GA = 1; else{:}\ GA = 0 \qquad Eq.S25$$

$$If(MA = 1){:}\ if(Fc = 0\ \&Fcoll = 0\ \&Fip = 0\ \&\ SSM = 1){:}\ GA = 1;\ else{:}\ GA = 0 \qquad Eq.S26$$

If the gate is available, *GP* is set to gate instructions *"GI"* determined by the operational module. On the other hand, *GP* should set to the maximum opening position *"MP"* (12.5m for the Cheakamus dam) if the gate collapses, while *GP* is equal to zero if the gate fails in closed position. In case the gate is exposed to remain in place failure, *GP* should be equal to the last gate position *"LGP"* recorded, as shown in **Eq. S27**.

$$If\ (Fcoll = 1){:}\ GP = MP;\ If\ (Fc = 1){:}\ GP = 0;\ \ If\ (Fip = 1){:}\ GP = LGP;$$
$$If\ (GA = 1){:}\ GP = GI \qquad Eq.S27$$

POWER ACTUATOR MODULE

The power actuator module, shown in **Fig. S5**, represents the turbine components, which interact to determine the power releases according to the turbine instructions. The power actuator module components are summarised in **Table S5.**

Table S5. Power actuator module dynamic variables

Dynamic Variables	**Symbol**
Power unit availability	***PUA (binary)***
Turbine flow	***TF*** $(\boldsymbol{m^3/s})$
Head cover	***HC (binary)***
Generator	***GN (binary)***
Maximum head cover flow	***MHCF*** $(\boldsymbol{m^3/s})$
Maximum Turbine flow	***Tfmax*** $(\boldsymbol{m^3/s})$
Sill discharge	***Qsill*** $(\boldsymbol{m^3/s})$
Power flow conveyance	***PFC*** $(\boldsymbol{m^3/s})$

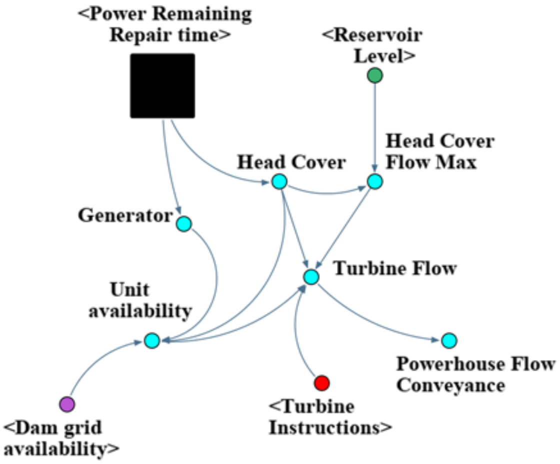

Fig. S5 Turbine Actuator Module component

This module is highly complex in real life; however, it has been simplified without affecting the model results accuracy to avoid model complexity and the large computational time. As such, the two main components being considered in this module are Power unit availability *"PUA"* and Turbine flow *"TF"*. The power unit is considered available if the turbine components are working properly, including Headcover *"HC"* and Generator *"GN"*. According to the hazard impact, *HC* and *GN* are considered unavailable for the Power components remaining repair time, determined by the multi-hazard module. *PUA* should also consider dam grid availability *"DGA"* if it is affected by hazard impact. (See, **Eq. S28**)

$$If\ (HC = 1; GN = 1): PUA = 1; else\ PUA = 0 \qquad Eq.S28$$

If the power unit is available, the unit can release the turbine flow equal to the turbine instructions. However, no turbine flow is released if the *GN* is unavailable. Also, if the *HC* fails, the maximum headcover flow *"MHCF"* is released, as shown in **Eq. S29**.

$$If\ (PUA = 1){:}\, TF = TI;\ \ If(PUA = 0\ \&\ GN = 0){:}\, TF = 0;$$

$$If(PUA = 0\ \&\ HC = 0){:}\, TF$$

$$= MHCF \qquad Eq.S29$$

MHCF is a site-specific relationship to be determined by the system modeler. In this model, *MHCF* is assumed to be five times the maximum turbine flow for the current reservoir level *"TFmax"* considering that the intake gate should be opened, as shown in **Eq. S30**. However, if this value (5**TFmax*) makes the *RL* drop below the sill level (363.06 m), *MHCF* is adjusted to *"Qsill"* to reduce the flow passing into the power tunnel from the reservoir. Moreover, If the gate collapses, no flow is released to the power unit, as shown in **Eq. S30 and S31**.

$$If\ (IG = 0){:}\ MHCF = \min(5 * \ TFmax(RL), Qsill);\ \ else{:}\, MHCF = 0 \qquad Eq.S30$$

$$Qsill = \max(RS + IF - SGR - RS_{at\ RL=363.06}, 0) \qquad Eq.S31$$

As turbine flow is determined, power flow conveyance "*PFC"* equals the sum of the releases passes through each turbine unit (only one unit is considered in this model), as shown in **Eq. S32**.

$$PFC = \sum TF \qquad Eq.S32$$

***M**ULTI-HAZARD MODULE*

The multi-hazard module, shown in **Fig. S6**, represents the hazard type, impact time, and the corresponding failed system components. The power actuator module components are summarised in **Table S6.**

Table S6. Multi-hazard module dynamic variables

Dynamic Variables	**Symbol**
Hazard impact time	***IT (days)***
Hazard type	***HT (code)***
Componenet outage time length	***COTL (days)***
Gate remaining repair time (array)	***GRrt (days)***
Failed close remaining repair time	***FcRrt (days)***
Failed remain in place remaining repair time	***FipRrt (days)***
Failed collapse remaining repair time	***FcollRrt (days)***
Power remaining repair time (array)	***PRrt (days)***
Headcover remaining repair time	***HCRrt (days)***
Generator remaining repair time	***GNRrt (days)***
Other componenet remaining repair time (array)	***OCRrt (days)***
PLCRTU remaining repair time	***PLCRTURrt (days)***
Penstock remaining repair time	***PNRrt (days)***
Grid remaining repair time	***GDRrt (days)***
Sensor remaining repair time	***SRrt (days)***

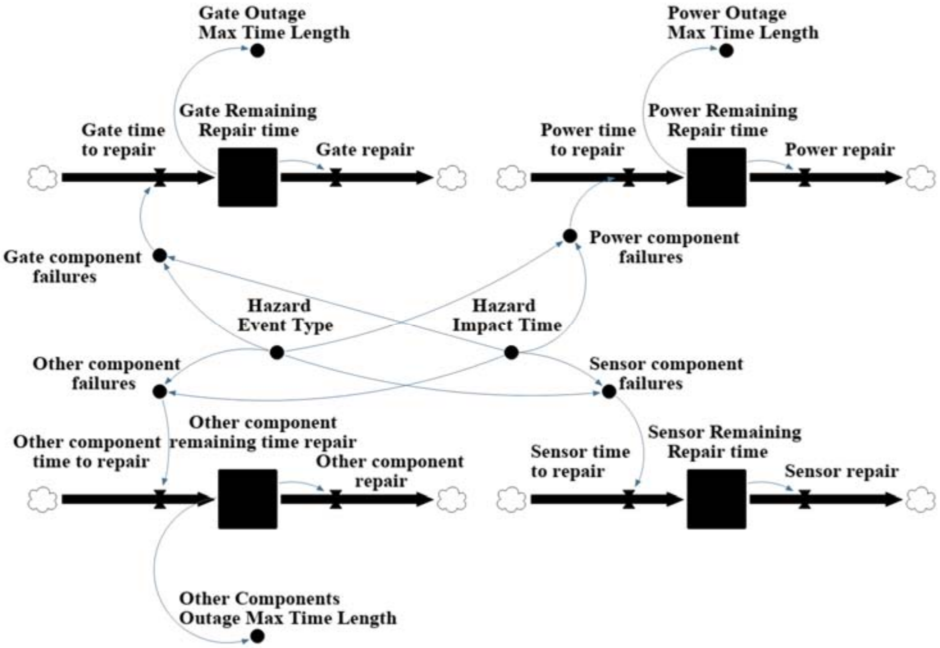

Fig. S6 Multi-hazard Module components

Hydropower system components that can be affected by the hazards have been divided into four groups: 1) Power components failure, including failure of head cover and generator; 2) Gate components failure, including components failure, leads to gate closure, gate collapse, and the gate remains in place; 3) Sensor's components failure including no-reading failure for the sensors; 4) Other components failure including communication equipment (i.e., *PLCRTU*), penstock rupture, and dam grid failure. Each group is simulated by a stock representing the components' remaining repair time, with an inflow defined by the time to repair, and outflow defined by the repair time. The stock and the two flows are defined as a dynamic array to represent its components (e.g., Power Components Remaining repair time *"PCRrt"* is an array with two elements, *PCRrt [0]* represent headcover component remaining repair time and *PCRrt [1]* represent generator component remaining repair time). The time to repair inflow rate is initiated at the hazard impact time" *IT"* and defined by the component outage time length *"COTL"* which represents the time length for the failed component to be out of service until it recovers according to the hazard event type *"HT"*. *COTL*, *IT,* and the sequence of the *HT* impacting the system are defined based on the generated multi-hazard scenario (see next section). *Outage Max Time Length* nodes represent the maximum remaining repair time of all components represented by the stock (e.g., Power Outage Max time Length is 20 days if the headcover is out of service for 10 days and the generator is out of service for 20 days). These nodes track the gate and turbine availability regardless of the failed component. It should also be noted that each type is simulated as an array that consists of different elements. Gate stock and flows are dynamic array which composed of three elements Failed close, Failed in place, and Collapsed, while Power stock and flows composed of two elements Head cover and Generator. Other component stock and flows consists of three elements PLCRTU, Penstock and Grid. The following equations **Eq. S33 and S34** are general for the four types of components affected by the hazards, where *X* refers to G (for Gate), P (for Power), S (for Sensor), and OC (for Other component).

$$\frac{d(XRrt)}{dt} = X\ time\ to\ repair - X\ repair \qquad Eq.S33$$

$$If\ (t = IT\ \&HT = N): Xcomponentfailure = COTL_N; else: Xcomponentfailures = 0 \qquad Eq.S34$$

*X*Outage Max Time length= Max (*X*Rrt [i]), where i is the elements of each *X*Rrt array

<u>DYNAMIC RESILIENCE MODULE</u>

The dynamic resilience module, shown in **Fig. S7**, represents the dynamic variables used to determine the change in system performance and subsequently calculate system resilience based on the developed resilience quantification approach. The dynamic resilience module components are summarised in **Table S7.**

Table S7. Dynamic resilience module dynamic variables

Dynamic Variables	**Symbol**
System performance	$\boldsymbol{P_{(Y)}(t)}$
Initial system performance	$\boldsymbol{P_{0\,(Y)}(t)}$
System performance state	$\boldsymbol{SPS_{(Y)}(binary)}$
Deduct	$\boldsymbol{Dt_{(Y)}(binary)}$
System performance losses	$\boldsymbol{\rho_{(Y)}(t)}$
System performance losses at the previous step	$\boldsymbol{\rho_{(Y)}(t-1)}$
Current hazard impact time	***CIT (t) (days)***
Current hazard impact time at the previous step	***CIT (t-1) (days)***

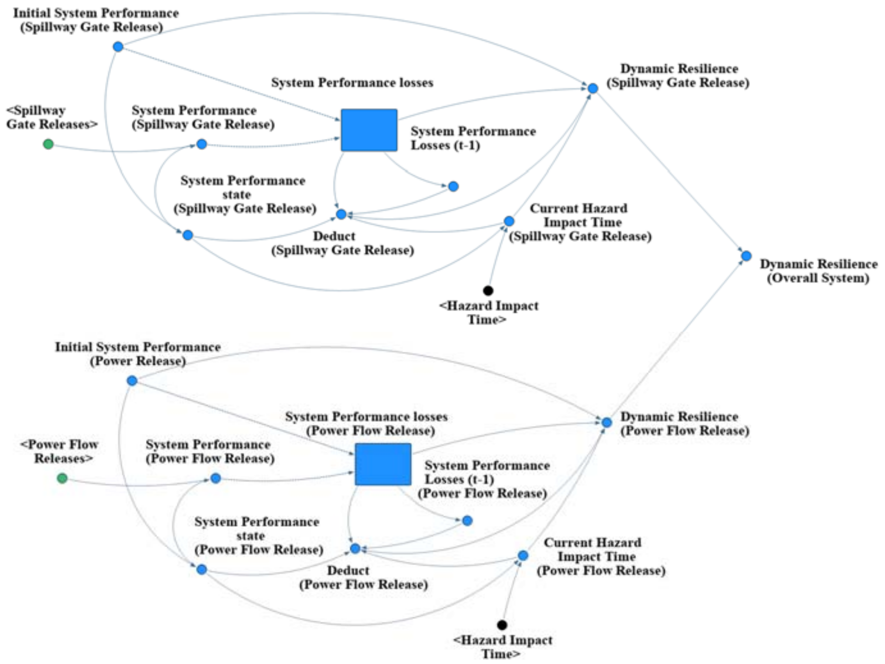

Fig. S7 Dynamic Resilience Module components

Within this demonstration example, the module quantifies overall system dynamic resilience corresponding to the spillway gates releases that may refer to the loss of system functionality to ensure irrigation or fish flow demands and power flow releases that may refer to the losses in system functionality to ensure hydropower generation demands. For the two components (Power flow releases and Spillway gate releases), System performance (*P(t)*) is calculated based on **Eq. S1** (in the original manuscript) as the ratio between the actual and the designed releases. In this demonstration example, the designed releases are assumed to be the spillway gates and power releases in normal operations without any hazards. It should be noted that in the real-life of dams, system performance metrics are not usually a simple function in the flow values; however, it may refer to the hydropower or irrigation demands (depends on dam multi-purposes) with upper and lower allowable limits, which may also vary with time along the year. However, due to the unavailability of the detailed system objectives/demands, this demonstration example considers the designed system outputs equal to the output in the normal operations (in case of no hazards). The change in system performance stock subsequently accumulates the system performance losses ($\rho_{(t)}$) starting from the current hazard impact time (t_0). Current hazard impact time *"CIT"* is updated by the hazard impact times *"IT"* for each hazard event, considering that the hazard event changes the system performance state *"SPS"*. As explained previously, for consecutive hazard events, where the secondary hazard occurred after the system is recovered from the primary hazard impact, System performance losses ρ_t should be calculated for each hazard separately. As such, Deduct node *"Dt"* is responsible for subtracting the system performance losses at the previous step "$\rho_{(t-1)}$" from the accumulated system performance stock value for the dynamic resilience calculation at the start of the secondary hazard impact time. Subsequently, the Dynamic Resilience node can estimate the system resilience at each time step for each component based on **Eqs. S4-S9** in the original manuscript. Then, the System Dynamic Resilience node computes the overall system dynamic resilience by integrating the two dynamic resilience nodes for each component based on **Eq. S10** in the original manuscript.

The following equations **Eq. S35, S36, and S37** are applicable for both spillway gates and power flow releases resilience quantification, where *Y* is general symbol that refers to Spillway releases and Power flow releases. It should also be noted that *P(t)*, *ρ(t)* and *r(t)* regarding Spillway and Power flow releases and the overall system resilience *R(t)* are calculated using **Eq. S4-S9** stated in the original manuscript.

$$If\ \left(\left|P_{0(Y)}(t) - P_{(Y)}(t)\right| > 0\ \right): SPS_{(Y)} = 1; else\ SPS_{(Y)} = 0 \qquad Eq.S35$$

$$If\ \left(SPS_{(Y)} = 1\right): CIT_{(Y)}(t) = IT(t); else\ CIT_{(Y)}(t) = IT(t-1) \qquad Eq.S36$$

$$If\ \left(CIT_{(Y)}(t) \neq CIT_{(Y)}(t-1) \&\& SPS_{(Y)} = 1\right): Dt_{(Y)} = \rho_{(Y)}(t-1);\ else: Dt_{(Y)} = 0 \qquad Eq.S37$$

CHEAKAMUS SD MODEL VALIDATION

The Cheakamus dam SD model is validated with the actual dam and the SD model constructed by King, 2020 outputs under different normal operations using the historical inflow data from 1967-1998 adopted from BC. Hydro, 2002. As shown in **Fig. S8 and S9**, the median curve of the power flow release and the total outflow of the SD model show a good agreement with the median of the numerical output of King, 2020 and the median of the actual values of the Cheakamus hydropower dam.

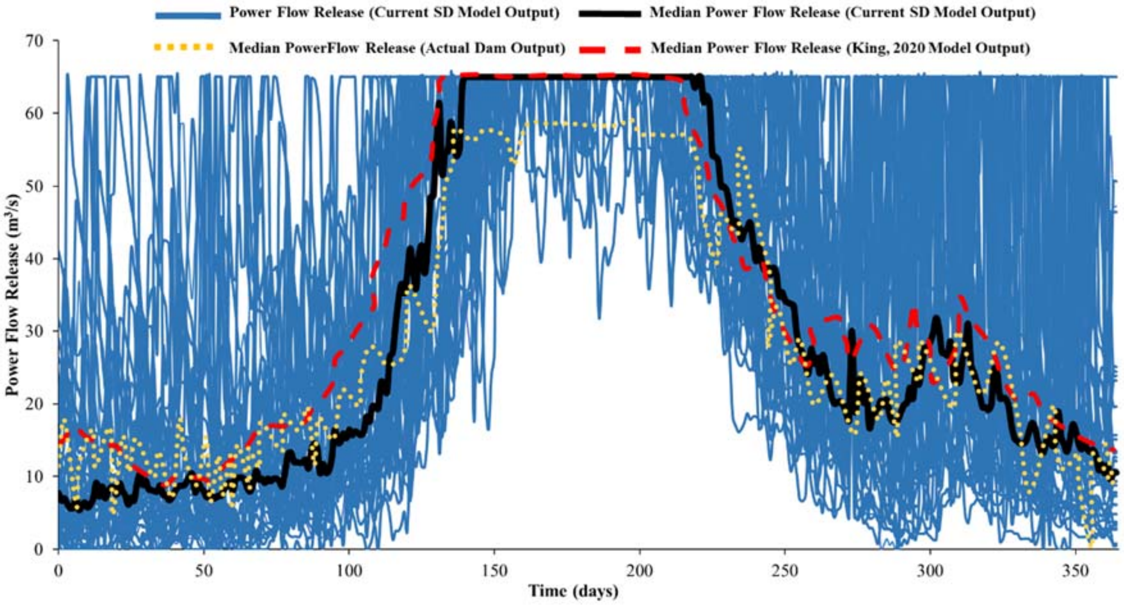

Fig. S8 Power Flow Release Validation

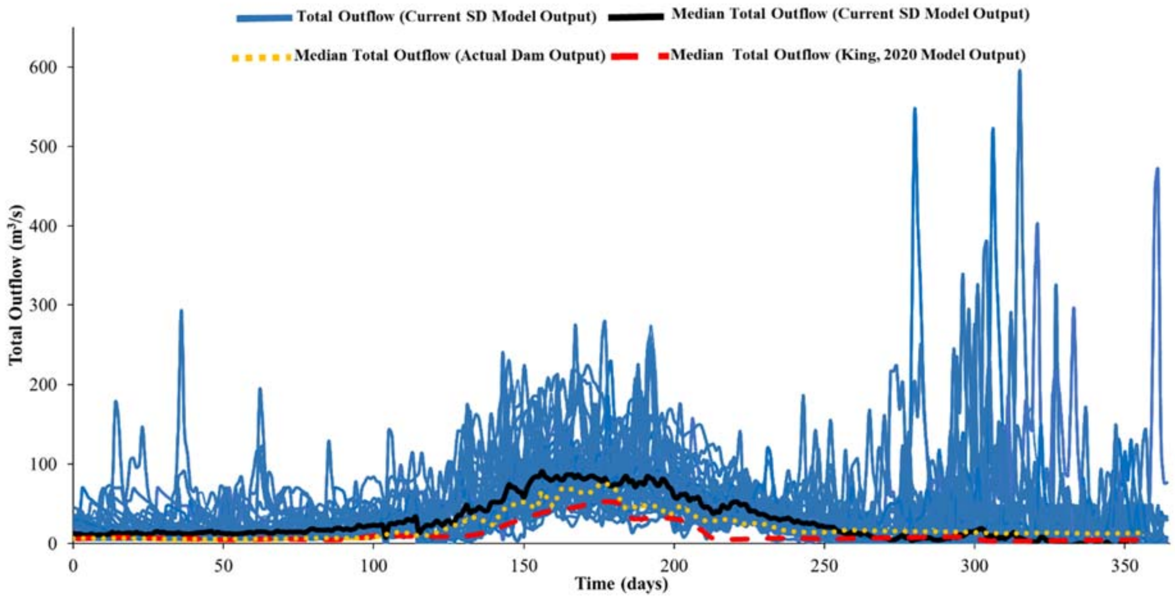

Fig. S9 Total Outflow Validation

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